HIGH CURRENT RF ACCELERATOR FOR FEL APPLICATIONS

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INTRODUCTION

The feasibility of basing free electron lasers in space depends upon reducing the size and weight of all system components to manageable levels. Two of the largest and most complex subsystems in any FEL concept are the accelerator and wiggler. Improvements in these two subsystems can provide a very high payoff.

Only two types of accelerators hold promise for high power FELs: the induction linac and the rf accelerator. Both types can produce the high quality (i.e., high brightness and monoenergetic), high voltage (of order 100 to 200 MeV) electron beams needed to drive the FEL wigglers.

Of these two, the induction linac concepts suffer size disadvantages because they are designed with relatively low accelerating field, "real estate" gradients and often use very heavy magnetic materials in acceleration cavities. Their advantage over most rf accelerator concepts is that they produce higher currents. These higher currents (of order a few kiloamps) can simplify the FEL wiggler subsystem by allowing it to operate as a single pass amplifier. At the lower currents typical of existing rf accelerator concepts, the wiggler must be configured as a master oscillator that requires a large and complex ring resonator and either grazing incidence optics or gas lenses.

If an rf accelerator can produce currents similar to an induction linac (i.e., 1 to 2 kA) while retaining the high brightness characteristic of rf devices, then the best features of both accelerator types can be combined. The high current rf linac (HCRF) concept proposed here has such advantages. The principal additional advantage is that cryogenics are not required. All other space-based rf concepts being considered today use superconducting technology to achieve high real estate gradients. We will show in this paper that the HCRF concept can achieve an average gradient of order 20 MV/m using standard conductors and low Q cavities. Therefore, relatively "low technology," robust construction techniques can be used for the accelerator. Risk is reduced accordingly.

The HCRF design is described in the next section. Initial analysis of two critical issues, beam loading and stability, are treated in the sections following. The concept utilizes high peak power (approximately 10 GW) microwaves to drive low Q rf cavities. The cavities are designed to selectively dampen modes that lead to transverse beam instabilities in the accelerator. The high power microwaves (HPM) will be generated in external devices such as phase-locked magnetrons or klystrons driven by relativistic electron beams (REBs). A parallel, lower voltage (approximately 1 MeV) accelerator will produce the REBs to drive the HPM devices. The HCRF accelerator will produce a 200 MeV FEL quality electron beam with 2 kA, 50 ps micropulses contained 50 A (average current), 2 μs macropulses repeated at 5 kHz (duty factor = 10^{-2}). An alternate design uses a shorter (500 ns) macropulse repeated at 20 kHz to produce the same 10^{-2} duty factor. Average electron beam power into the wiggler will be 100 MW in both designs.

HCRF LINAC CONCEPT: MOTIVATION AND DESIGN PARAMETERS

Most space-based free electron laser concepts employ superconducting rf accelerators driving wigglers that are configured as master oscillators. Superconducting rf accelerators have higher real estate gradients than their conventional room temperature counterparts but are limited to rather low average currents in the macropulse because of transverse beam instabilities.

The transverse instabilities are proportional to the loaded Q for the transverse modes. In general, the higher the Q for the fundamental mode, the higher the Q will be for the transverse modes, and the more difficult the problem of suppressing transverse instabilities. The peak micropulse current in high Q superconducting rf accelerators is limited by single bunch wake-field effects. The longitudinal, axisymmetric wake-field causes energy spread and loss and the transverse, dipole fields degrade emittance. Wake-field effects are a strong function of the fundamental driving frequency and depend superlinearly on the inverse of the aperture size. Wake-field effects limit the micropulse current to a few hundred amps (~ 200) in standard designs with a fundamental driving frequency of 500 MHz. Beam breakup instabilities limit the average current during the macropulse to less than 1 amp.

Lawrence Livermore National Laboratories and NRL have developed a theory and experiment for alternate wiggler configurations that are designed to operate as high gain single pass amplifiers.[1] These configurations require high peak currents in the micropulse. Currents on the order of 2 kA are optimal to achieve high extraction efficiency and suitable guidance control of the optical pulse within the FEL wiggler. In the past, only induction accelerators were thought capable of generating the high peak micropulse currents required for the high gain single pass wiggler. However, induction accelerators have very low real estate gradients (on the order of less than 1 MV per meter), and are relatively heavy and large. The challenge is to achieve high peak micropulse currents with a compact (high accelerating field gradient), room temperature, rf accelerator design that avoids transverse beam instabilities and efficiently converts rf to electron beam energy.

The proposed solution to this challenge utilizes high peak power rf sources (3 to 10 GW per source) to drive the HCRF accelerator. The HCRF operates at room temperature and employs low Q cavities. Transverse instabilities are suppressed with damping probes and a segmented cavity design to spoil the Q for dangerous modes. Because of the low Q cavity design, very large apertures are possible: much larger, in fact, at a given fundamental frequency than the corresponding aperture size for the superconducting cavity designs. Hence, wake-field effects are reduced sufficiently at a fundamental driving frequency of 500 MHz to allow acceleration of 2 kA or more current in the micropulse without emittance degradation or energy spread.

The HCRF accelerator concept is shown schematically in Fig. 1 and the temporal pulse format of the electron beam is shown in Fig. 2. This figure describes the micropulse, the macropulse,

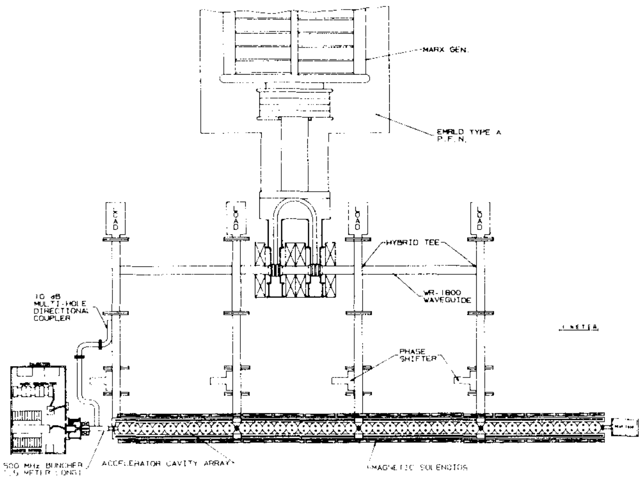

Fig. 1. Schematic of the 200 MeV, 2 kA HCRF Linac. Magnetron driver, phase-locked magnetrons, rf feed, injector, cavities and beam dump represented.

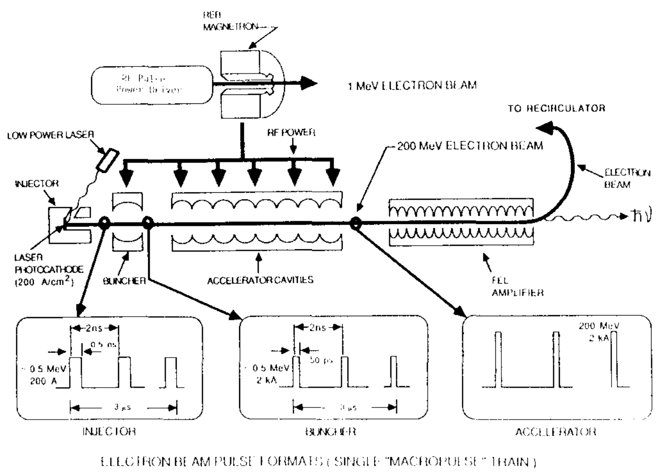

Fig. 2. Temporal pulse format of HCRF.

and also shows the evolution of the wave train as it moves through the injector, the buncher, and the accelerator. A key feature of the concept is that the rf accelerating structure is driven by a very high power microwave source. In fact, the recent development at Physics International of gigawatt-level S-band magnetrons and the demonstration that two such sources can be phase-locked through mutual coupling makes the HCRF accelerator concept feasible.

The injector design for this concept is based upon the recent work on high brightness, high current electron guns developed by both LANL and Thermal Electron Corporation. Basically, a low power laser is used to irradiate a suitable photocathode (Cs_3 Sb) that can provide from 200 to 500 A/cm^2 of emitted current density. The injector is powered by a low voltage (200 to 500 keV) electron gun. The low power laser is Q-switched and mode-locked to the rf accelerating power train; it can also serve as the seed laser for the wiggler.

The injector of Fig. 1 would produce a 0.5 MeV, 200 amp (~ 1 cm^2 area) photocathode power train. The power train consists of a macropulse on the order of 500 ps duration. The micropulse occurs at every period of the rf micropulse. Using a 500 MHz rf frequency and filling every rf bucket gives the train of micropulses, shown in Fig. 2, repeating every 2 ns for the duration of the macropulse.

The next device in the accelerating structure is the buncher. The buncher is an rf cavity that impresses a ramp on the accelerating pulse so that the tail of the micropulse can catch up to the head. For example, a 60 kV ramp in a 0.5-meter-long buncher is sufficient to bunch the initial 500 ps pulse to 50 ps (Fig. 1) and still restrict the energy spread in the fully accelerated pulse to less than 0.75%. The pulse leaves the buncher with approximately the same 500 keV peak electron energy, but the peak current is increased to 2 kA. The macropulse enters the high gradient accelerating cavities after passing through a beam conditioning section (not shown) to clean up the rise and fall of the micropulses.

The accelerating cavities provide the final energy amplification. For the example of Fig. 1, the endpoint energy is 200 MeV and the peak current in each 50 ps micropulse is 2 kA. To obtain the desired average electron beam power, the macropulse is repeated at the required frequency. For 100 MW average power in the electron beam and a 200 MeV endpoint energy, one needs an average current of 0.5 amp. This is achieved by repeating the micropulse train with the characteristics of Fig. 2 at a repetition rate of 20 kHz for a 0.5 µs long macropulse or 5 kHz for a 2 µs long macropulse. A summary of these parameters is given in Table 1.

TABLE 1: Summary of Fundamental Beam Parameters:
Average electron beam power, 100 MW

- Voltage = 200 MeV
- Peak Micropulse Current = 2 kA
- Average Current in Macropulse = 50 to 100 A
- Input RF Frequency = 500 MHz
- Repetition Rate = 1.6 to 3.3 kHz (3 µs macropulse duration)
- Duty Factor = 10^{-2}

The relativistic magnetron that powers both the accelerator cavities and buncher furnishes rf energy at a rate sufficient to maintain a 10 GW average beam power for the full 0.5 to 2 µs macropulse. For 90 to 95% beam loading, a single magnetron or group of phase locked devices supplying approximately 11 to 12 GW with a pulse width of 0.5 to 2 µs coupled into a low-loss waveguide network, can power such a beam. Our most current design is derived from the 500 MHz, center fed, superconducting five-cell structure at CERN.

BEAM LOADING

In order to sustain high gradients and to efficiently convert rf to beam kinetic energy while still keeping the wall losses in the room temperature HCRF cavity structure manageable, the beam loading (i.e., the fraction of stored rf energy taken out by the beam) must be > 90%. Results of an analysis of the attainable accelerating efficiency are given in Fig. 3 along with many of the salient characteristic parameters of the accelerating cavities. Here the efficiency is the product of: 1) the beam loading fraction, 2) the ratio of the duration of the accelerating phase (total rf pulsewidth minus the fill time) to the total rf pulse duration, and 3) the transmitted to incident rf power ratio. With this definition the efficiency scales directly with both the beam loading and the rf pulse duration. The optimal VSWR is 1.2. The most auspicious dependence is the increase in efficiency with macropulse current shown in Fig. 3. Values of efficiency near 80% are feasible. With an assumed shunt impedance of R/Q = 320 Ω/m, and a beam loading of 95% the concomitant intrinsic Q value is 23750. The associated CW wall losses (with 50 A in the macropulse) are 526 kW/m, quite near demonstrated levels.

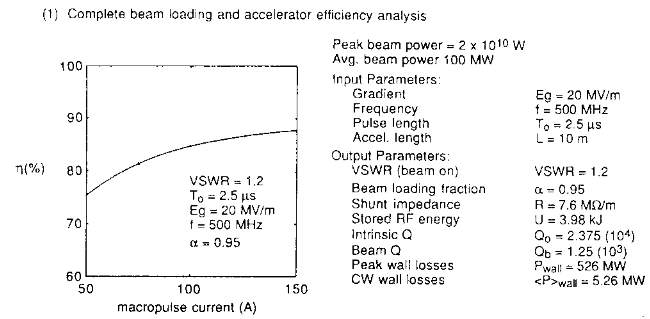

Fig. 3. Results of initial beam loading analysis.

STABILITY

Initial estimates of the immunity of the HCRF linac design to several varieties of the beam breakup instability are promising. Regenerative beam breakup is an oscillation within a single accelerating section due to the interaction of the beam with a dipole mode. For a standing wave structure, the critical current (for a continuous beam) above which this instability can be expected is:

$$I_R = 0.25 \frac{\lambda^2 Eg}{Q_\perp L} .$$

For the parameters: Eg = 20 MV/m, L = 10 m, λ = 0.6 m and a higher order mode Q value, $Q_\perp$ = 100, I_R = 180 A. For a beam pulse of finite length, τ_p, the starting current is increased by more than a factor of 3. In either case, this critical current is well above the expected HCRF macropulse currents of 50 to 100 A.

The mechanism for the cumulative beam breakup is quite different. In a multi-section accelerator each section provides a small increase in the amplitude of the beam displacement. For a level of higher order modes similar to that assumed above, the critical current is $I_c \approx$ 140 A. If required, strong focusing can increase this critical current by factors of two or more.

The approach to guarantee stability to these effects is to reduce the Q-value of the higher order modes (HOM). Prior to constructing the 500 MHz accelerator we plan to assemble and test a proof-of-principle S-band accelerator. This accelerator will be driven by our existing 3 GW, 2.8 GHz magnetrons. With this device the relative effects of 1) HOM damping probes and 2) advanced cavity designs (Fig. 4) on $Q_\perp$ will be evaluated.

Simple estimates of the energy spread due to longitudinal wake-field effects yield $\Delta E/E \approx$ 1.8% (at the peak of the rf cycle). With this figure, one computes that the beam must be injected ~ 6.5° ahead of the rf peak to obtain the desired range $\Delta E/E \lesssim$ 0.5%. Beam pulse shaping is being investigated as a means to further reduce the spread in energy.

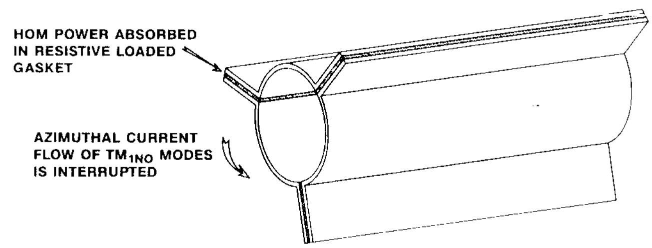

Fig. 4. Advanced cavity design which cannot support azimuthal rf currents.

SUMMARY

The HCRF linac is a fundamentally new accelerator concept for driving space-based FELs. The potential technical advantages of the HCRF linac approach over the alternative superconducting rf accelerator approach as a space-based FEL driver are:

1. Compactness and ruggedness,
2. No cryogenics necessary, and
3. Simpler allowed wiggler configuration.

The two principal technical milestones will be the successful matching of the high power microwave sources to the standing wave structure, and demonstration of an effective HOM suppression scheme.

REFERENCE

1. P. Sprangle, Cha-Mei Tang, and W. M. Manheimer, "Nonlinear Theory of Free-Electron Lasers and Efficiency Enhancement," Phys Rev. A, Vol. 21, No. 1, January 1980.